Simulation of Descaling during Continuous Hot Rolling

Oscar Zapata, Martha P. Guerrero-Mata, and Rafael Colás

Universidad Autónoma de Nuevo León, Facultad de Ingeniería Mecánica y Eléctrica, Ave. Universidad S/N, Cd. Universitaria, San Nicolás de los Garza, N.L. C.P. 66450 MEXICO.

Abstract: *Oxidation of the steel surface is always present during hot rolling and the oxide has to be eliminated before deformation to avoid imprinting and damaging the surface. It is normal practice to use high pressure water jets (descaling) to break and remove the oxide layer formed at different stages. The design of the descaling stations is carried out by trail and error without a systematic way to confirm the benefits of a given design. A model was developed using the commercial software ABAQUS™/Standard in order to evaluate the mechanical integrity of the secondary oxide found on low carbon steel during hot rolling. A thermo elastic analysis was carried out into 4 zones: 1)exit of the tunnel furnace and entrance to descaling, 2) water blanket zone, 3) zone of descaling, low and high pressure headers and 4) exit of the descaling and entrance to rolling to evaluate the temperature gradient between oxide and steel. The stress state within the oxide layer was determined, assuming three different oxide thicknesses, the oxide layer was considered to be homogeneous and composed only of wustite (FeO). The numerical results obtained were compared with experimental data taken from plant, showing that the model can be used as means of evaluating different descaling designs.*

Keywords: Low carbon steel, oxide scales, hot rolling.

1. Introduction

Oxidation of the steel surface is always present during hot rolling. It can be beneficial in some cases as shallow surface defects can be removed by light oxidation during reheating, a pehomena known as self descaling, but the oxide crust has to be eliminated before the material is deformed to avoid the imprint, and the consequently damage of the steel surface and wear of the work rolls (Gebara, 2002). It is normal practice to use high pressure water jets (descaling, Figure 1) to break and remove the oxides formed at different stages of the hot rolling process (Kizu, 2001).

The oxides formed during the different stages of the hot rolling are the primary scale formed during reheating in the rolling mill furnace; the secondary scale is formed after descaling during and after the roughing operations. Generally this scale is easily removable before it enters the finishing mill, and the tertiary scale is formed during final rolling before and in between the stands of the finishing mills.

Oxidation of steel during hot rolling begins with a linear growth of an initial iron oxide (scale), this is controlled by the gas phase transport of oxygen to the surface of the steel, after reaching certain oxide thickness the growth rate changes to parabolic, this rate is controlled by diffusion of iron through the scale layer. The later continues until stresses in the oxide layer are big enough to produce cracks and voids (Nelson, 2006).

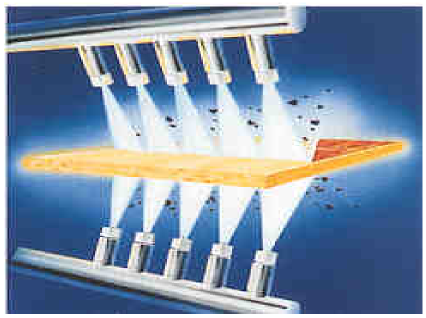


Figure 1. Descalingby high pressure water jets.

The oxide layer in unalloyed steels formed at temperatures above 570°C is made of different species: wustite (FeO), around 90%, magnetite (Fe_3O_4), around 8%, and hematite (Fe_2O_3) the remaining 1 to 2%. Growth of each species, or that of the whole layer, starts linearly following a parabolic growth, as below (Basabe, 2004, Krzyzanowski, 2003, 2004):

$$e = kt^{0.5}$$

where ***e*** is the thickness of the oxide layer, ***t*** the time and ***k*** a temperature dependent growth coefficient. Descaleability depends on the mechanical properties of the scale (oxide layer). Table I shows the thermophysical properties of the oxide phases at high temperature. There are various modes of scale cracking, spalling, blistering, flaking and delamination (Gebara, 2002, Li, 2002).

Hot rolled steel strip in a CSP (compact steel processing) line is produced in facilities that include continuous casting of thin slabs, hot direct charging into continuous tunnel furnaces and direct rolling to the required dimensions, allowing the production of strips of gauges thinner than 1 mm. Figure 2 shows an schematic diagram of a compact line, the steel is cast into slabs of 48 to 52 mm in thickness, that are cut into the required length, and are fed into continuous holding tunnel furnaces that equalize the temperature of the piece to that of rolling, between 1050 and 1150°C. Casting and rolling operations are also regulated by means of the tunnel furnaces as the casting speed ranges from 2.5 to 6 m/min, whereas the slabs are fed into the rolling mill at speeds that range from 15 to 40 m/min. Removal of the oxide crust can be a problem in CSP lines, since the surfaces of the slabs are only descaled after the slabs exit the tunnel furnace and before it is fed into the rolling mill.

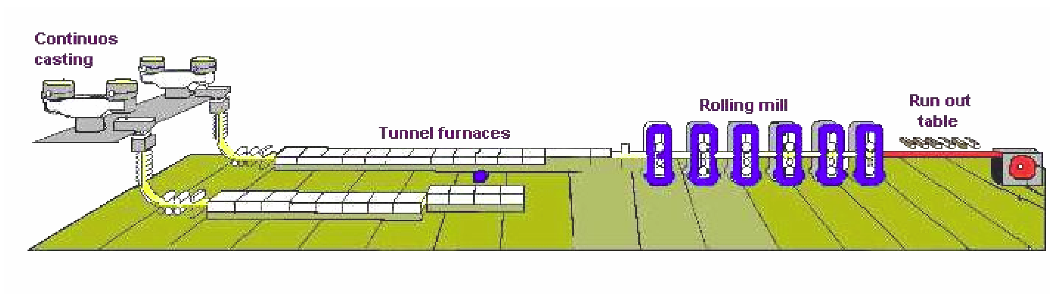


Figure 2. Schematic diagram of a CSP line (Ramírez-Cuellar, 2004).

The descaling capability is a function of the force of water applied over a concentrated area. The factors which influence descaling efficiency, such as water cleanliness, spray interference, spray overlap, descale speed, etc., can all be addressed through sound design engineering practices, together with an operating and maintenance program that ensures descaling system performance is optimized at all times. Increasing descaling capability is the solution generally adopted worldwide for the control of secondary scale defects.

A design of descaling systems includes header arrangement, nozzle selection and layout, flow rates and operation pressures, all aimed at controlling scale removal. Occurrence of defects can be diminished largely through improvements to the descaling system capability.

Table 1. Thermophysical properties of oxide phases (Wolf, 2000).

Property	Wustite	Magnetite	Hematite	Units
Density	5,670	5,180	5,240	kgm^{-3}
Tensile strength	0.4	4	10	MPa
Hardness	270-350	420-500	1,000	HV
Thermal conductivity	2.7-3.2	0.5-3.5	0.5-3.5	$Wm^{-1}K^{-1}$
Thermal diffusivity	0.7e-6	0.2-3 e-6	0.2-3 e-6	m^2s^{-1}
Specific heat capacity	58	200	150	$Jmol^{-1}K^{-1}$

2. Simulation

The model is designed for removal of secondary scale; descaling is carried out in a station with four headers, two on top and two on the bottom, the front pair operates at low pressure (21 MPa) and the back pair at a higher pressure (30 to 38 MPa). Symmetry was taken in account for simulation and only half the model was constructed. A sheet thickness of 52 mm and a length of 120 mm were used, three oxide thicknesses before descaling were taken into account, the oxide film was considered to be homogeneous and composed only of wustite (FeO) and complete adhesion of oxide to steel was assumed. The considered oxide thicknesses were: e_1=500, e_2=750 and e_3=1000 µm. These thicknesses were chosen from the results found from previous work (Ramírez, 2004, Sun, 2004, Torres, 2000). A constant speed of the steel while rolling was used, 0.342 m/s.

The thermal-elastic analysis was carried out into four zones, Figure 3. Zone I: Exit of the tunnel furnace and entrance to descaling. Zone II: Water blanket. Zone III: Zone of descaling, low and high pressure headers. Zone IV: Exit of the descaling and entrance to rolling. Figure 4 shows the distances used for each zone.

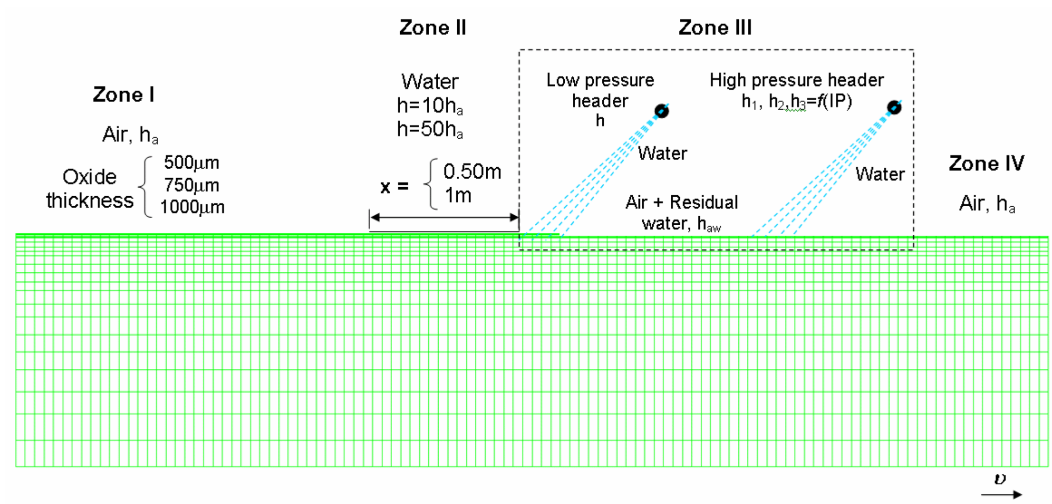


Figure 3. FEM mesh using Abaqus/Standard.

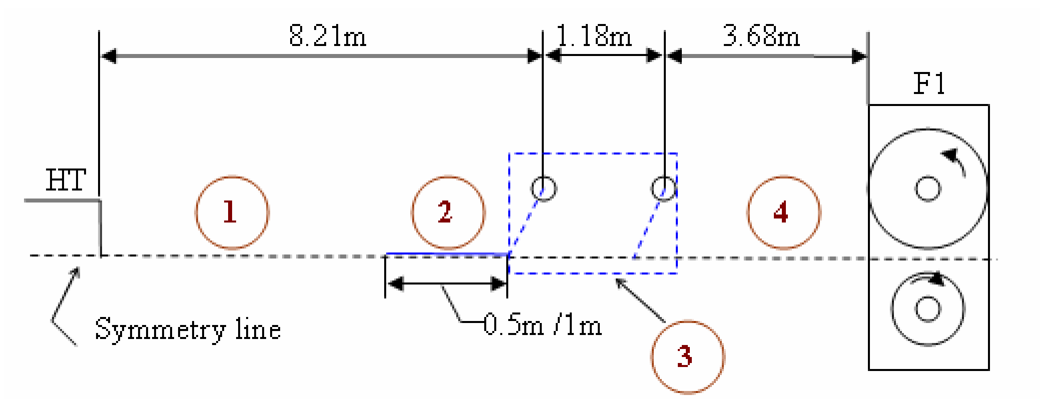


Figure 4. Distance used in the four zones (Ramírez-Cuellar, 2000).

2.1 Zone I and Zone II

The heat transfer coefficients for Zone I was that for still air at 35ºC, h_a=21.2 W/m^{2}ºC, and for water at 25ºC. Two options were taken for Zone II, as this zone is affected by the presence of water on the oxide surface before entering the descaling zone. The length of this zone is represented by a distance ***x***, and for each ***x***, two different values of heat transfer coefficient were taken, h_1=10h_a and h_2=50h_a. Emissivity of the oxide, ε_{FeO} was considered to be 0.6.

2.2 Zone III

A heat transfer coefficient due to convection and boiling water is used to produce the effect of air and residual water between the two headers, h_{AW}=185 W/m^{2}ºC, radiation is neglected in this zone. The heat transfer coefficient for the headers was calculated according to the following equation (Wook, 2002, Li, 2005):

$$h = (4.4265IP + 7.3670) \times 10^4 \qquad (1)$$

where IP is in Bar and it is the impact pressure of the water on the oxide scale.

Table 2. Heat transfer coefficients for the headers (Ramírez-Cuellar, 2000).

Header	Impact pressure (MPa)	h (kW/m^{2}ºC)
Low pressure	0.71	387.951
High pressure	0.69 0.88 1.08	379.098 463.202 551.732

2.3 Zone IV

Radiation is turned on for the slab as it comes out from the high pressure header zone, emissivity is taken as ε_{Fe}=0.8. Heat transfer for air convection is the same as for Zone I.

2.4 Stresses

The stresses that the oxide crust is subjected to can be calculated as a function of the physical properties and dimensions of both steel and oxide, and by the difference in temperature between the surface of the oxide and that of the slab (Krzyzanowski , 2004, Ramírez-Cuellar, 2004, Yu, 2002). In this case the stresses from one zone to the next one were calculated using the information from the last step calculated. Equations 2 and 3 were used with the values shown in Table 3.

Table 3. Values used for the oxide stress calculation (Ramírez-Cuellar, 2000).

T_{ox} in ºC, E_o=240Gpa, n=-4x10^{-4}ºC^{-1}

Parameter	Steel	Oxide
α (K^{-1})	15.3x10^{-6}	12.2x10^{-6}
E (GPa)	2x10^{11}	$E_o(1+n(T_{ox}-25))$
v	0.3	0.33

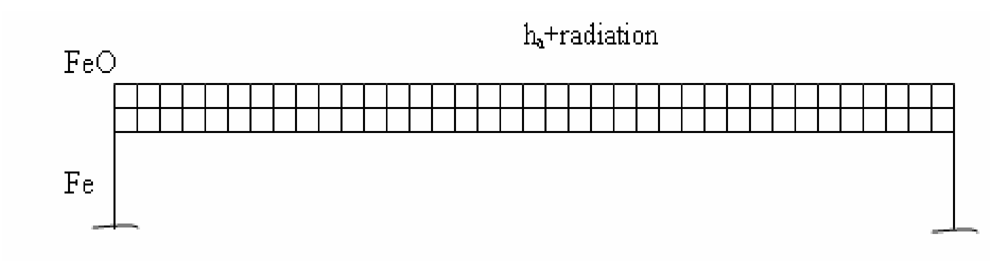
$$\sigma_{ox} = -\frac{(\alpha_{ox} - \alpha_m)(T_L - T_H)E_{ox}}{(1-v_{ox})\left(1+\frac{E_{ox}}{E_m}\frac{e_{ox}}{e_m}\right)} \qquad (2)$$

$$\sigma_m = \frac{(\alpha_{ox} - \alpha_m)(T_L - T_H)E_m}{(1-v_m)\left(1+\frac{E_m}{E_{ox}}\frac{e_m}{e_{ox}}\right)} \qquad (3)$$

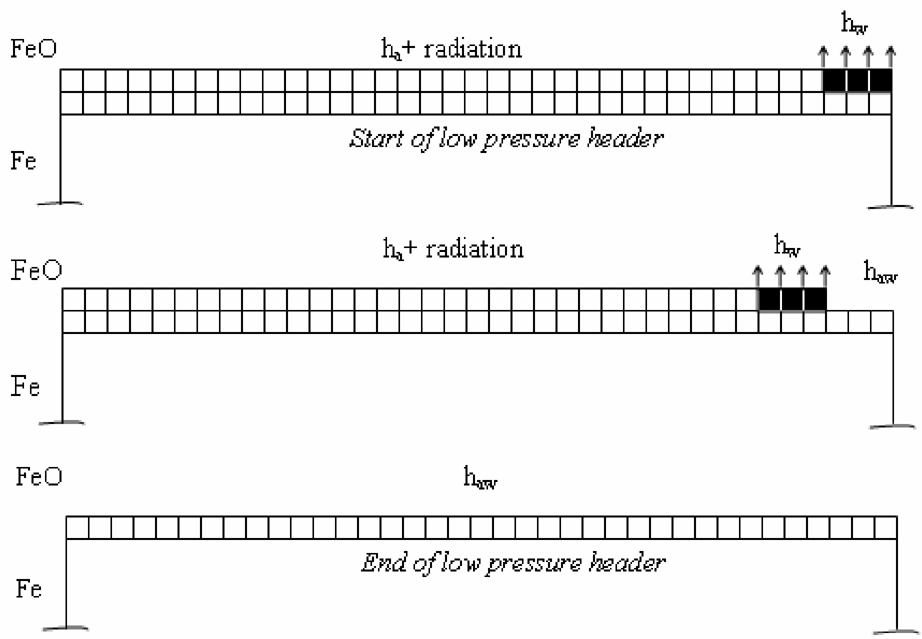
2.5 Steps for the model.

CPE4RT element type was used in the model, 2310 elements for the steel sheet and 1870 for the oxide layer. Four steps were defined in the input file in order to model the four zones of the descaling process, as below:

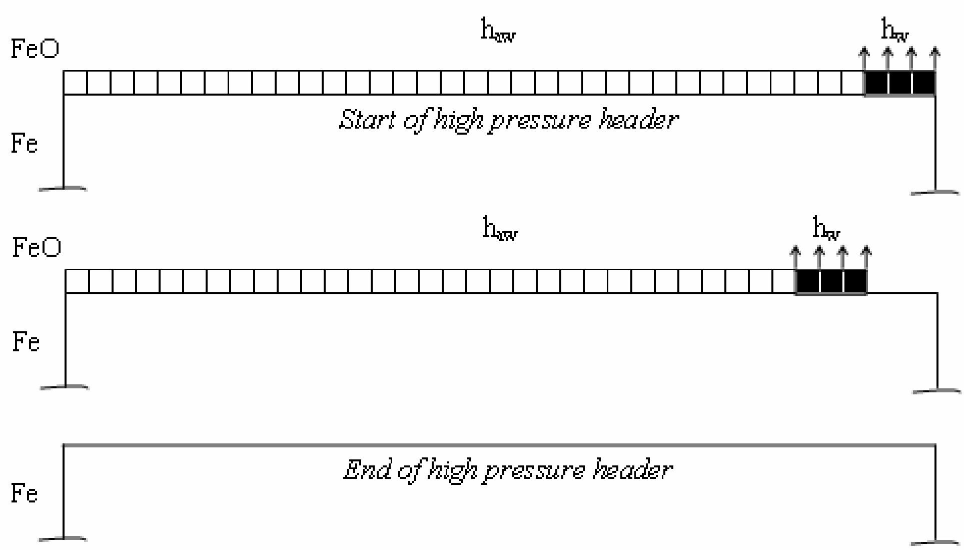
Step 1:Heat transfer analysis from tunnel furnace to first descaling mill.



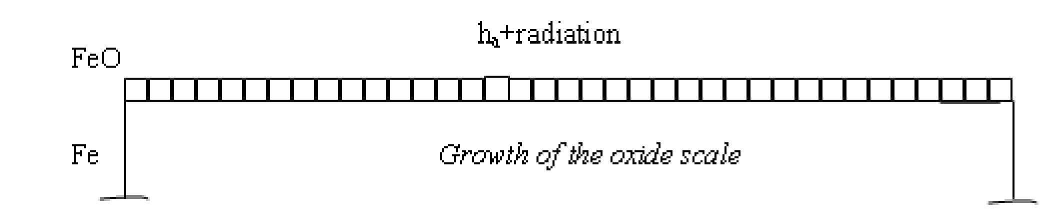
Step 2: Descaling analysis. (Deactivation of elements)



Step 3: Heat trasfer analysis from low pressure header to high pressure header.



Step 4: Heat transfer analysis from descaling just before entering to rolling.



Step 5: Stress analysis before entering to the first rolling mill.

3. Results

Figure 5 shows the temperature distribution before descaling at three different locations along the strip thickness, without and with the oxide layer of 500 μm, this was modeled to confirm that the oxide layer acts as a thermal barrier on the strip surface. Figure 6 presents the temperature lost on the strip surface for the different oxide thickness.

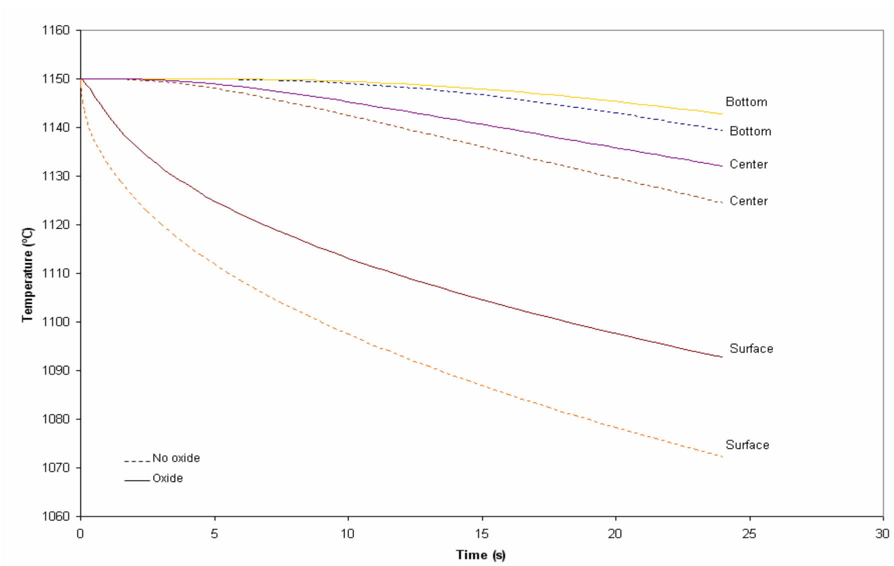


Figure 5. Temperature changes in Zone I for the strip with and without oxide layer at different locations of its thickness.

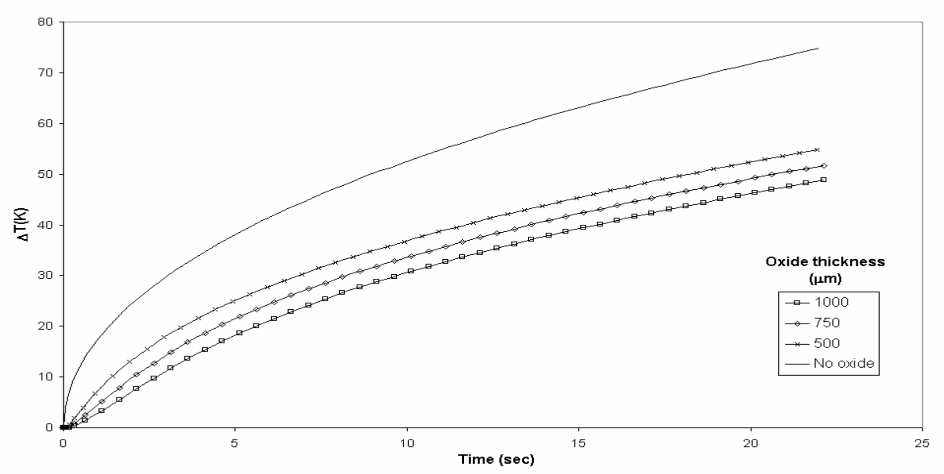


Figure 6. Temperature drop on the strip with and without oxide layer with the three different thickness used, Zone I.

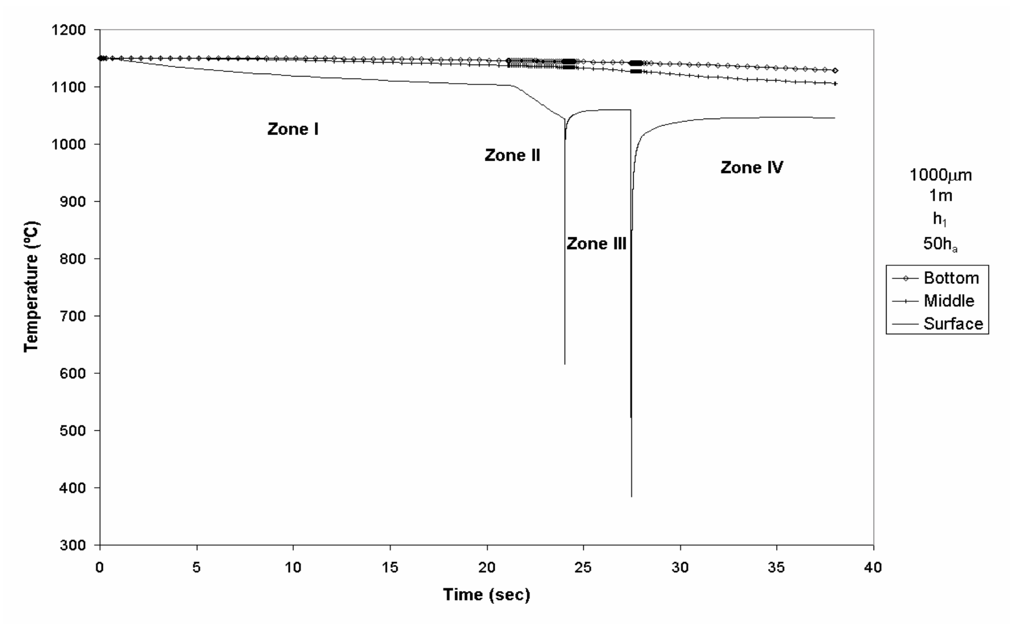


Figure 7. Temperature changes along the strip thickness for the four zones modeled.

The temperature evolution along the four zones at the interface oxide/steel and through the strip thickness is presented in Figure 7. The oxide crust will be removed below the line presented in Figure 8 of critical stress for breaking of the oxide, all of the stresses predicted by the model granted the complete removal of the oxide layer.

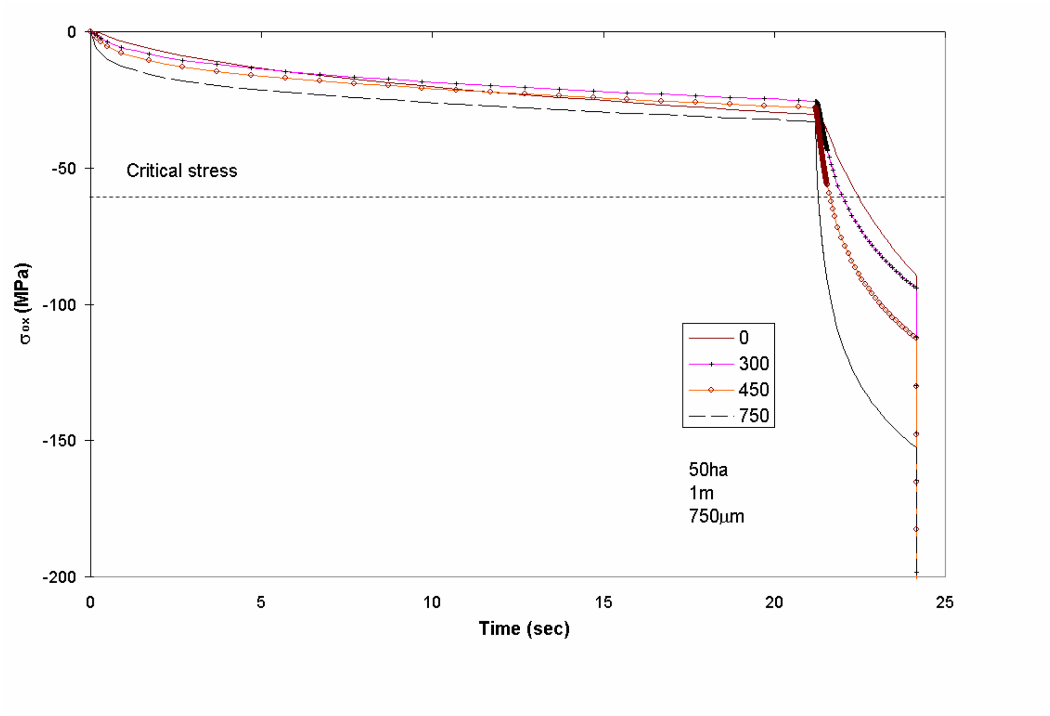


Figure 8. Stress distribution for oxide thickness 750μm, comparison with critical stress for descaling, for *x*=100cm.

4. Conclusions

The temperature and stress distributions predicted by the model are in agreement with those reported in the literature.

The use of adequate thermal and mechanical properties has a great impact on the final results.

The percent of oxide removed was an imposed condition, therefore for the adequate removal a criterion depending on header pressure and geometrical conditions of the oxide layer should be involved.

5. References

1. Basabe, V.V. and J.A. Szpunar, "Grow Rate and Phase Composition of Oxide Scales during Hot Rolling of Low Carbon Steel", ISIJ International, Vol. 44, No. 9, pp. 1554-1559, 2004.
2. Gebara, G. and P. Ceolin, "Control of Rolled in Scale Defects at Dofasco's Hot Strip Mill", 44th MWSP Conference Proceedings, Vol. XL, pp. 1067-1076, 2002.
3. Kizu, T., Y. Nagataki, T. Inazumi and Y. Hosoya, "Effects of Chemical Composition and Oxidation Temperature on the Adhesion of Scale in Plain Carbon Steels", ISIJ International, Vol. 41, No. 12, pp. 1494-1501, 2001.
4. Krzyzanowski, M., C. M. Sellars and J.H. Beynon. "Characterization of oxide scale in thermomechanical processing of steel", Thermomechanical Proc: Mechanics, Microstructure and Control, pp. 94-102, 2004.
5. Krzyzanowski, M., W. Yang, C.M. Sellars and J.H. Beynon. "Analysis of Mechanical Descaling: Experimental and Modelling Approach". Materials Science and Technology, Vol. 19, pp. 109-116, 2003.
6. Li, Y.H. and C. M. Sellars. "Cracking and Deformation of Surface Scale During Hot Rolling of Steel". Materials Science and Technology, Vol. 18, pp. 304-311, 2002.
7. Li, Xuetong, Minting Wang and Fengshan Du. "A coupling thermal mechanical and microstructural FE model for hot strip continuous rolling process and verification". Materials Science and Engineering A 408 (2005) 33-41.
8. Mukhopadhyay, A., I.C. Howard and C. M. Sellars. "Development and Validations of a Finite Element Model for Hot Rolling using ABAQUS/STANDARD". Materials Science and Technology, Vol. 20, pp. 1123-1133, 2004.
9. Nelson, B.D., G. Gebara and J. Tiley, "Design Criteria for Descaling at Dofasco's No. 2 Hot Mill", Iron and Steel Technology, Vol.3 No. 8, pp. 72-79, 2006.
10. Ramírez-Cuellar, J., M. P. Guerrero-Mata, L. A. Leduc and R. Colás. "Modelling descaling during hot rolling of steel". J. Phys. IV France, Vol. 120, pp. 209-215, 2004.
11. Sun, W., A.K. Tieu, Z. Jiang, H. Zhu, and C. Lu. "Oxide scales growth of low-carbon steel at high temperatures". Journal of Materials Processing Technology Vol. 155-156, pp. 1300-1306, 2004.
12. Torres, M. and R. Colás. "A model for heat conduction through the oxide layer of steel during hot rolling". Journal of Materials Processing Technology, Vol. 105, pp. 258-263, 2000.
13. Yu, Y. and J. G. Lenard. "Estimating the Resistance to Deformation of the Layer of Scale During Hot Rolling of Carbon Steel Strips". Journal of Materials Processing Technology Vol. 121, pp. 60-68, 2002.
14. Wolf, M.M., "Scale Formation and Descaling in Continuous Casting and Hot Rolling part II", Iron and Steelmaker, Vol. 27, No.6, pp. 65-66, 2000.
15. Wolf, M.M., "Scale Formation and Descaling in Continuous Casting and Hot Rolling part VI", Iron and Steelmaker, Vol. 27, No.6, pp. 22-24, 2000.

16. Wook, J. and J.W. Choi, “Convective heat transfer coefficient for high pressure water jet”, ISIJ International, Vol. 42, No. 3, pp. 283-289, 2002.

6. Acknowledgments

The authors acknowledge the financial support provided by the Consejo Nacional de Ciencia y Tecnología (CONACYT), México, Programa de Apoyo a la Investigación Científica y Tecnológica (PAICYT 2006) – UANL and the facilities to carry out the experimental data recollection to the Steel Company Ternium prior Hylsa, S.A. de C.V.